

MATERIALS AND MANUFACTURING PROCESSES  
FOR INCREASED LIFE/RELIABILITY

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During the early 60's, improvements in both quality and durability of disk raw material were considered necessary for both military and commercial engines. Vacuum melting technology proved to be the breakthrough that spawned a new series of "superalloys", but it offered many process challenges. These new, tougher to forge alloys were developed to run at stress levels 50% above then existing commercial disk experience and simultaneously meet greatly increased low cycle fatigue life capabilities. After addressing to the low probability of being able to rely on Non-Destructive Testing (NDT) to sort for "good" parts - including the then emerging improved ultrasonic techniques - General Electric set an objective to provide material free of harmful indications for engine parts.

The challenge was met by introducing an entirely new concept in raw material process control which was defined as Premium Quality (PQ) material. It imposes careful selection, screening and sampling of the basic alloy ingredients, followed by careful monitoring of the melting parameters in all phases of the Vacuum Melting (VIM/VAR) sequence. Special care is taken to preclude solidification conditions that produce adverse levels of segregation. Melt furnaces are routinely cleaned and inspected for contamination. Ingots are also cleaned and inspected before entering the final melt step.

The ingot to billet conversion steps are closely controlled and monitored to maintain melt traceability and ingot position. Special Non-Destructive Evaluation (NDE) routines are applied to the final billet. Questionable indications are cut out for metallurgical evaluation. Disposition of such a billet depends on the nature, frequency and distribution of the indication. Occasionally an entire ingot, or even the entire heat, is rejected.

Billets that meet standards are then sent to the forging house where those to be used for rotating disks undergo further NDE. Those passing this stage are cut into forging multiples - each multiple producing one part - and the end faces of each multiple are etched as a final check for segregation before forging begins. When unacceptable indications are observed, correlation is made to the location of the affected billet in the ingot, and if not found to meet certain criteria, the entire ingot product is again subject to rejection.

Forging and heat treat operations are performed to very detailed practices with tight controls on forging pre-heat and reduction schedules, as well as the quench rates from solution heat-treatment. Metallurgical control is maintained over morphology, grain size and mechanical properties. Once accepted as Premium Quality material, the disks are shipped to the shop and skim-cut to a configuration suitable for immersion ultrasonic inspection. A three-mode scan is performed with Numerically Controlled (NC) equipment capable of finding randomly oriented indications in the part. Rejections are less than one part in one thousand for significant ultrasonic indications, and few of these have proven to be actual flaws.

These processing and inspection actions on the part of the supplier and manufacturer provide reasonable assurance that high quality parts are delivered. As a result, General Electric CF6 engines have not experienced a materials related failure of a fan, compressor or turbine disk where the prescribed controls have been followed.

**PREVENTION OF ROTOR FAILURES IS A PRIMARY OBJECTIVE OF  
THE ENGINE MANUFACTURER.**

**MATERIAL PROCESS CONTROL IS THE MOST IMPORTANT KEY ELEMENT  
IN THE PREVENTION OF MATERIAL DEFECT RELATED FAILURES.**

**BACKGROUND**

**THE HIGH BYPASS TURBOFAN ENGINE PRESENTED MANY  
NEW CHALLENGES TO ROTOR MATERIALS INTEGRITY NEEDS:**

- 50% INCREASE IN MECHANICAL PROPERTY LEVELS**
- MORE MASSIVE COMPONENTS**
- MAINTAIN DESIGN MARGINS (BURST/LCF)**
- MAINTAIN VERY HIGH RELIABILITY**
- EXTENDED LIFE REQUIREMENTS**
- COMPLETE KNOWLEDGE OF OPERATING STRESS  
AND ENVIRONMENT**

**GE ROTOR MATERIAL INTEGRITY PERSPECTIVE**

**IN MORE DETAIL**

**MATERIAL DEFECT EXPERIENCE**

**I. LOW NUMBER OF "MATERIAL DEFECT"**

**RELATED CRACKS IN COMMERCIAL**

**ENGINE ROTOR EXPERIENCE**

**COMMERCIAL ENGINE ROTOR EXPERIENCE (1962-1975)**

**MATERIAL DEFECT RELATED FLAWS**

**GE - FLAWS FOUND IN FIELD ROTORS**

	<b><u>NUMBER</u></b>	<b><u>INITIAL FLAW SIZE</u></b>
● ROTOR FLAWS	20	0.25 - 2.5 INCHES
● UNCONTAINED INCIDENTS	1	0.25 - 0.5 INCHES

**TOTAL INDUSTRY - SAE AD HOC COMMITTEE (SATTAR)**

- 137 UNCONTAINED DISK INCIDENTS
  - 19 (14%) MATERIAL DEFECT RELATED
- 38 OF THESE WERE SEVERITY CATEGORY III AND IV
  - 10 (26%) MATERIAL DEFECT RELATED

NDE EXPERIENCE

II. NDE IS A GOOD PROCESS CONTROL TOOL,  
BUT IS NOT AN ADEQUATE FINAL SCREEN.

NDE DETECTION CAPABILITY  
90% PROBABILITY

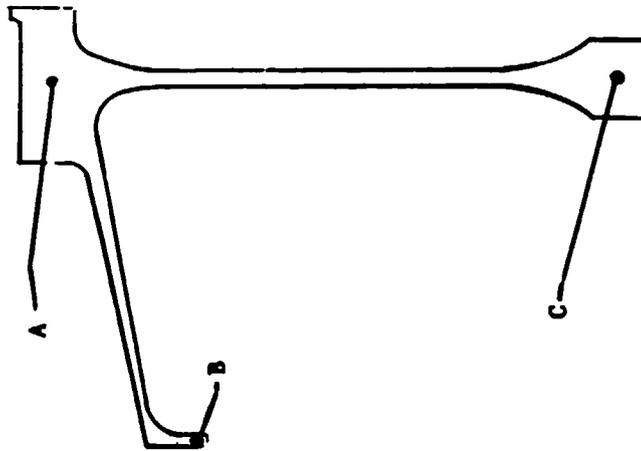
<u>SYSTEM</u>	<u>SEMI-CIRCULAR CRACK LENGTH (MILS)</u>	
	<u>50% CONFIDENCE CRACK SIZE</u>	<u>95% CONFIDENCE CRACK SIZE</u>
FPI	40	65
EDDY CURRENT	10	25
ULTRASONICS		
- NEAR SURFACE (1/4")	25	50
- BULK (2")	60	120
	351	

ULTRASONIC CAPABILITY

COMPARISON OF NEEDED VS REAL WORLD NDE CAPABILITY FOR ROTOR COMPONENTS

SEMI-CIRCULAR CRACK LENGTH (MILS)  
90% PROBABILITY

AREA	NEED FOR DESIGN LIFE	PRODUCTION (1) CAPABILITY (95% CONF.)	LABORATORY (1) CAPABILITY	LABORATORY (2) CAPABILITY
A	25	135	90	60
B	60	70	25	15
C	15	100	25	15
		NORMAL SENSITIVITY SCAN	HIGH SENSITIVITY SCAN	



(1) RANDOM FLAW ORIENTATION

(2) PREFERRED FLAW ORIENTATION

**NDE PROBLEMS**

**(ULTRASONIC INSPECTION)**

**EQUIPMENT - PRODUCTION EQUIPMENT PUSHED BEYOND LIMITS AT HIGH SENSITIVITY**

**DISKS - SURFACE FINISH/MICROSTRUCTURE PREVENTED HIGH SENSITIVITY INSPECTION**

**OPERATOR - MOST SYSTEMS MANUAL OPERATION, I.E. MANUAL SIGNAL RECOGNITION/EVALUATION**

**UTL SYSTEM - (OPERATOR/EQUIPMENT/PART) REQUIRED TO OPERATE BEYOND LIMITS**

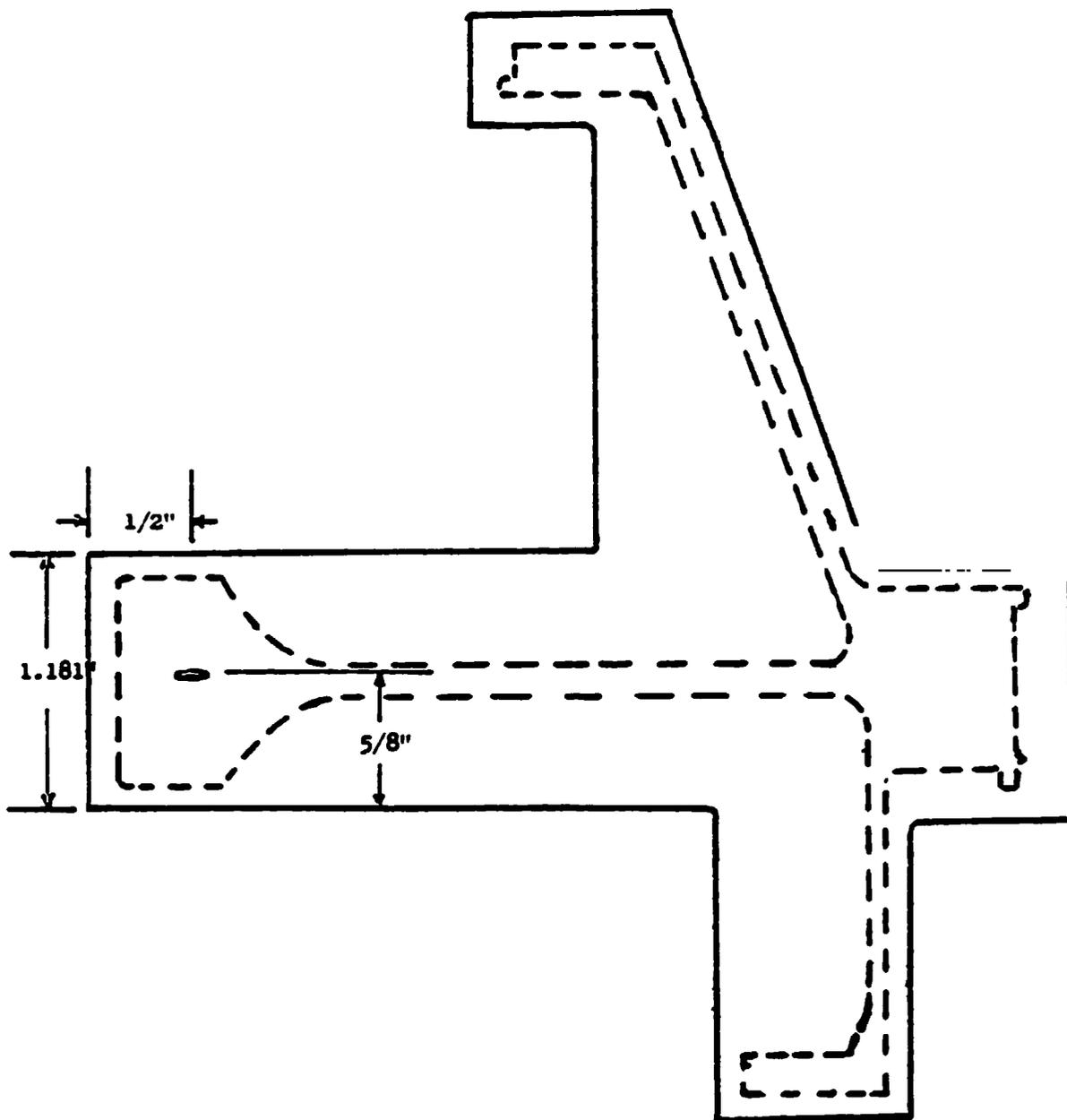
**TYPICAL NDE EXPERIENCE**

**ULTRASONIC INSPECTION**

<b><u>INSPECTION SOURCE</u></b>	<b><u>READINGS AS REPORTED BY OPERATOR</u></b>	
	<b><u>LOW SENSITIVITY</u></b> <b><u>AMP. % *</u></b>	<b><u>HIGH SENSITIVITY</u></b> <b><u>AMP. % *</u></b>
<b>INITIAL SCAN PRODUCTION</b>	<b>20</b>	<b>85</b>
<b>REPEAT SCAN PRODUCTION</b>	<b>10</b>	<b>80</b>
<b>NDT LAB PRODUCTION</b>	<b>8</b>	<b>35-55</b>
<b>NDT LAB ENGINEERING</b>	<b>10-12</b>	<b>55-60</b>

**80% AMPLITUDE = SIDE OF 20 MIL DIAMETER HOLE**

**\* DEFECT IN PREFERRED ORIENTATION FOR DETECTION**



CROSS-SECTION OF DISK SHOWING  
LOCATION OF FLAW

**GOALS FOR NDE CAPABILITY  
(90% PROBABILITY/95% CONFIDENCE)**

<b>PRODUCTION INSPECTION MODE</b>	<b>NEAR TERM GOAL FLAW SIZE, MILS</b>	<b>LONG TERM GOAL FLAW SIZE, MILS</b>
FPI	40	25
EDDY CURRENT	10	5
ULTRASONICS	20	5

● **MAJOR EFFORT AT GE TO IMPROVE ULTRASONICS**

- TRANSDUCER
- PULSER/RECEIVER
- SIGNAL ANALYSIS
- COMPUTER AIDED CONTROL/EVALUATION

GOAL: REMOVE OPERATOR JUDGEMENT FROM SYSTEM

**GE ROTOR MATERIAL INTEGRITY PERSPECTIVE**  
**RECAP**

- I. 50% INCREASE IN MATERIAL PROPERTIES PLUS INCREASE IN LIFE DEMANDS
- II. VERY LOW INCIDENCE OF MATERIAL DEFECTS
- III. MAINTAIN DESIGN MARGINS AND VERY HIGH RELIABILITY

**CONCLUSION:**

- WE HAVE EXPERIENCED VERY FEW MATERIALS RELATED DEFECT FAILURES.
- THE FACT IS WE ACHIEVE FAILURE PREVENTION BY MATERIALS AND MANUFACTURING CONTROL ---- JUST MAINTAIN IT.

**"PREMIUM QUALITY" MATERIAL AND PROCESS SPECIFICATIONS**

**P.Q. SYSTEM GOAL**

- MAINTAIN HIGH CONFIDENCE IN ESTABLISHED PROCESSES
- PREVENT MATERIAL DEFECTS

CONTROL PROCESS - PREVENT DEVIATION

AUDIT SYSTEM - ADEQUATE CONTROL/CORRECTIVE ACTION

AUDIT PROCESS - UNIFORM/CONSISTANT PRACTICE DRAWING

INSPECT PRODUCT - DRAWING CONFORMANCE  
- NDE AS A PROCESS CONTROL TOOL

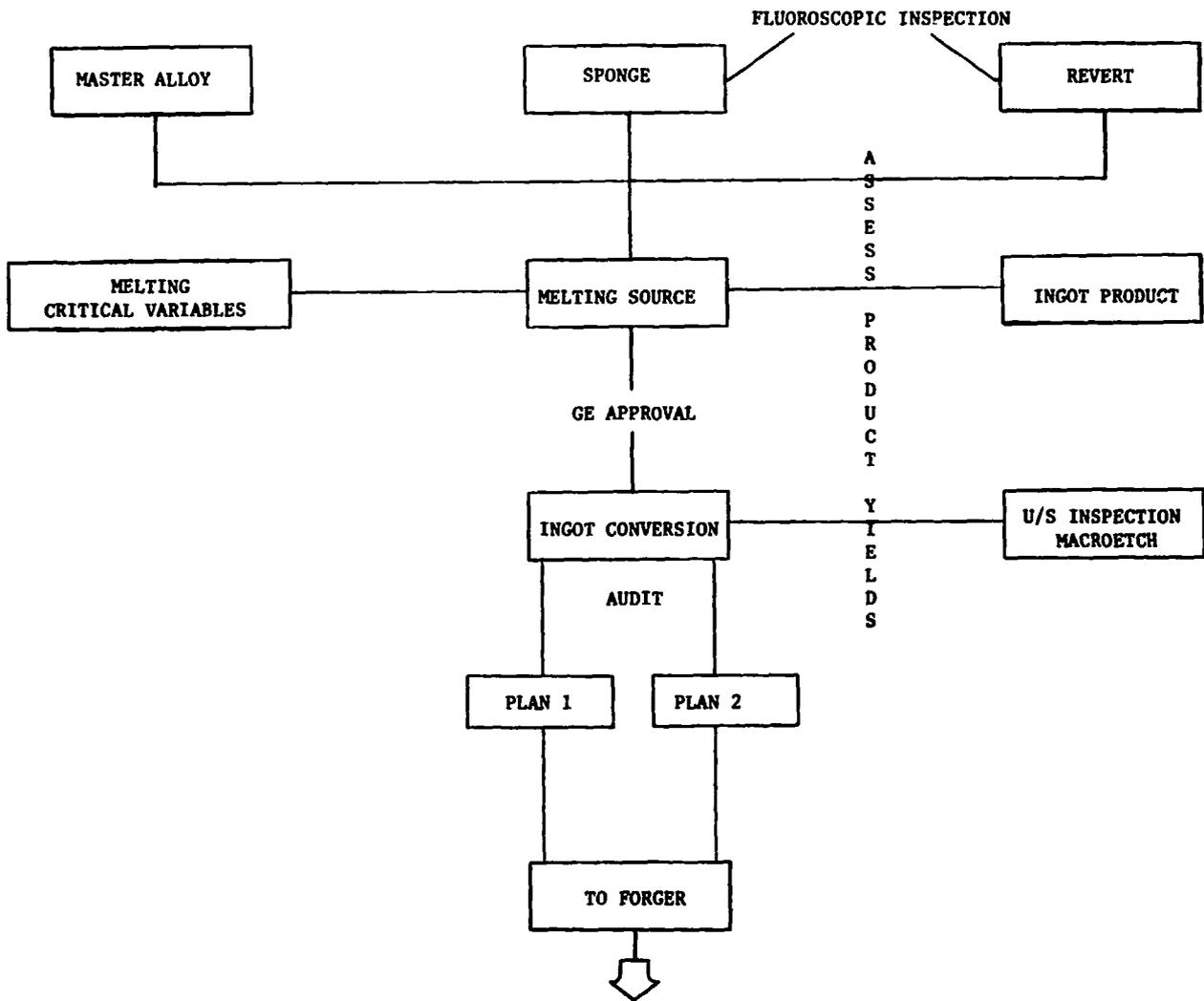
MAJOR EMPHASIS: EARLY PROBLEM RECOGNITION

**P.Q. MATERIAL SYSTEM**

**IN-DEPTH CONTROL FOR CRITICAL ROTATING PARTS**

- TRACEABILITY - ALL RAW MATERIAL
- DOUBLE OR TRIPLE VACUUM MELTING
- CONTROLLED MELTING AND CONVERSION
- BILLET AND FORGING MULTIPLE NDE
- FORGING AND HEAT TREATMENT
- FINISHED PART NDE
- APPROVED VENDOR LIST/REPORT CARD
- VENDOR AGREEMENT - PROCESS CHANGE APPROVAL
- DOWNGRADE VENDOR - POOR PERFORMANCE

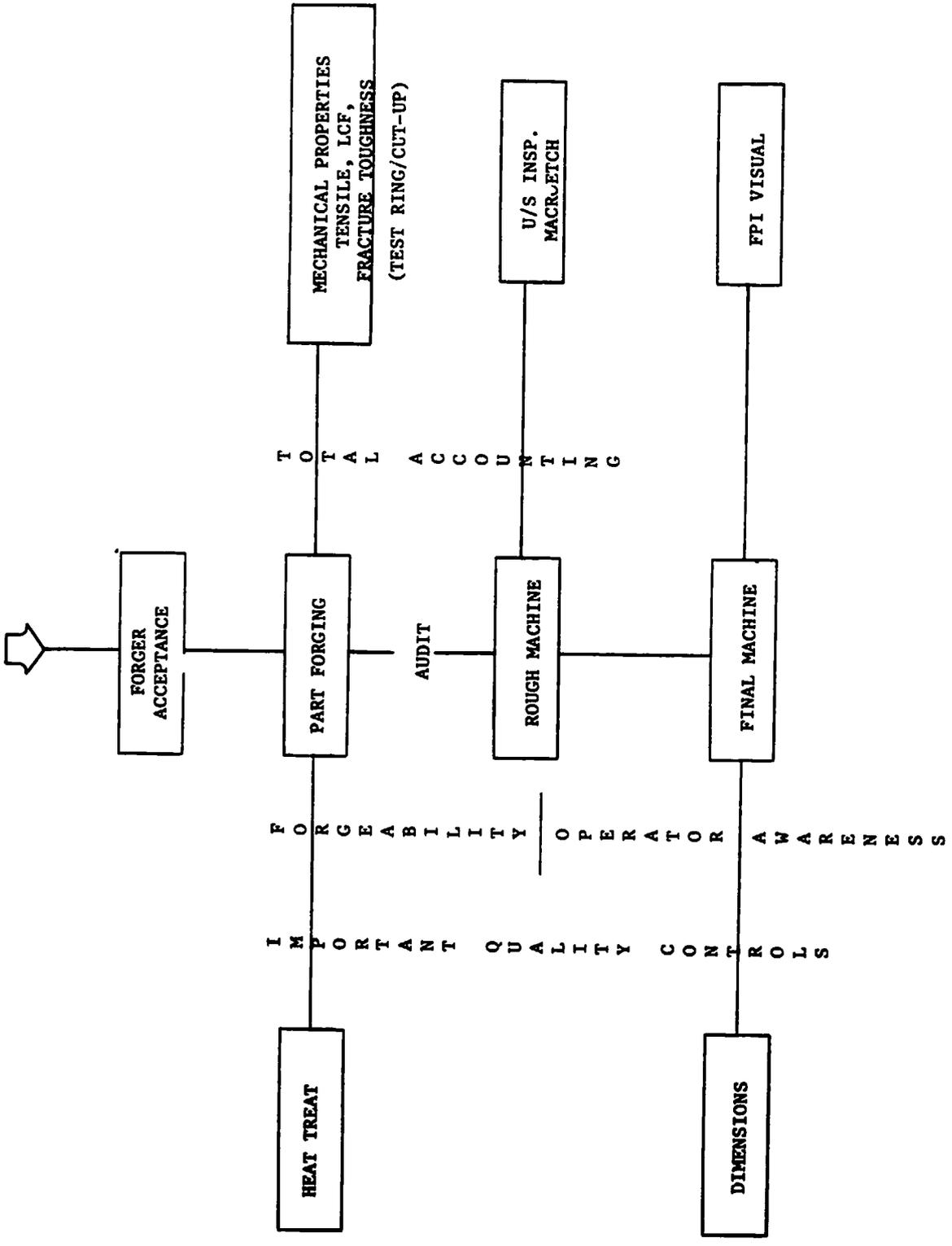
TITANIUM BASE ALLOY



PREMIUM QUALITY TITANIUM ALLOY CONTROLS

M  
I  
L  
L

- MELT RAW MATERIAL/SOURCES
  - TI SPONGE
  - MASTER ALLOY
  - REVERT ALLOY
  - TI DIOXIDE
  - COMPACT WELDING
- MELT FURNACE CLEANLINESS
- MELT INTERRUPTIONS/PRELIMINARY AND FINAL CYCLES
- VACUUM/WATER LEAKS
- REMELT ELECTRODE SURFACE CLEANLINESS
- INGOT CONVERSION PRACTICE
- BILLET ACCEPTANCE PLAN
  - ULTRASONIC INSPECTION PLAN
  - MACROETCH BAR ENDS
  - FORGE-DOWN PROPERTIES



PREMIUM QUALITY TITANIUM ALLOY CONTROLS

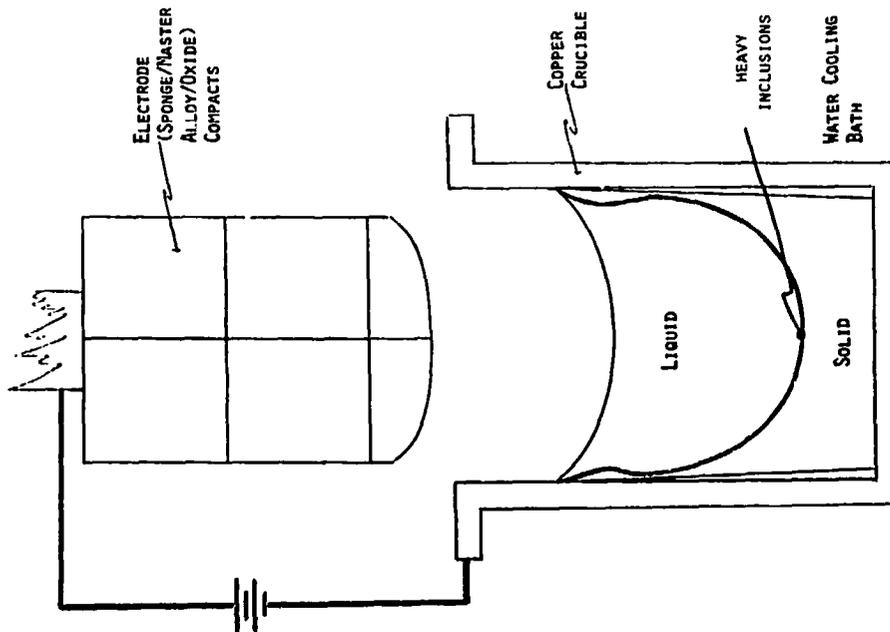
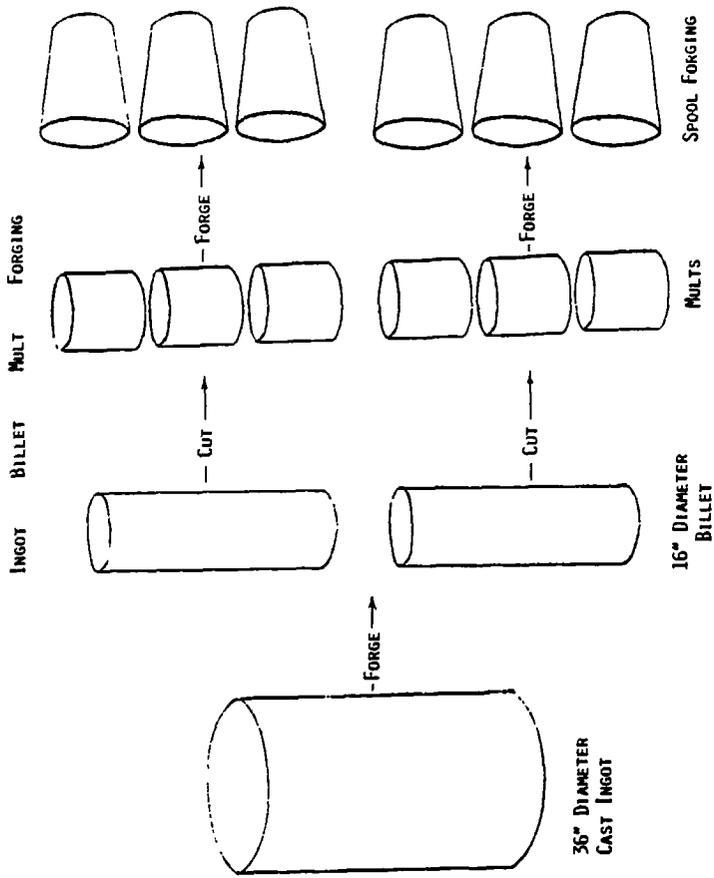
- FORGING MULTIPLE MACROETCH
- FORGING PROCESS
  - PRE-HEAT
  - UPSET RATIO
  - HEAT TREATMENT
  - MICROSTRUCTURE
  - MACROETCH
- MECHANICAL PROPERTIES
  - TENSILE
  - FRACTURE TOUGHNESS
  - LOW CYCLE FATIGUE
- PROCESS DOCUMENTATION
- TOTAL MATERIAL/PROCESS CONTROL
  - TRACEABILITY
  - ACCOUNTABILITY

TYPICAL TITANIUM MELTING PRACTICE

(SIMILAR PRACTICE FOR IRON AND  
NICKEL BASE ALLOYS)

TRIPLE VACUUM MELTED

- WELDED COMPACTS                      MELTED TO 24" DIAMETER ELECTRODE
- 24" DIAMETER ELECTRODE              MELTED TO 30" DIAMETER ELECTRODE
- 30" DIAMETER ELECTRODE              MELTED TO 36" INGOT



# A HORROR STORY

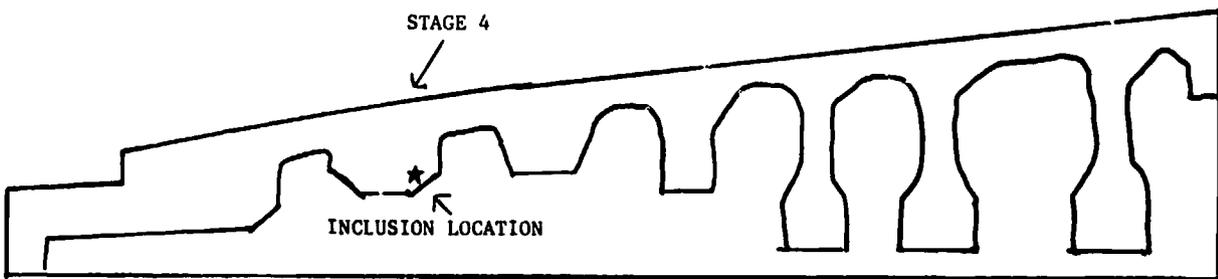
## INCIDENT:

● STAGE 3-9 Ti-6-2-4-2 SPOOL

- HARD ALPHA ZONE PLUS OXIDE INCLUSIONS

RESULT: A LATENT MELT RELATED HIGH OXYGEN ZONE PASSED THROUGH THE SYSTEM UNDETECTED.

STAGE 3-9 SPOOL CONTOUR



----- CENTER LINE -----

## ENGINE INCIDENT INVESTIGATION

### ● PRIMARY CAUSE

TYPE I OXYGEN STABILIZED HARD "ALPHA"  
INCLUSION WITH POROSITY

### ● FAILURE MECHANISM

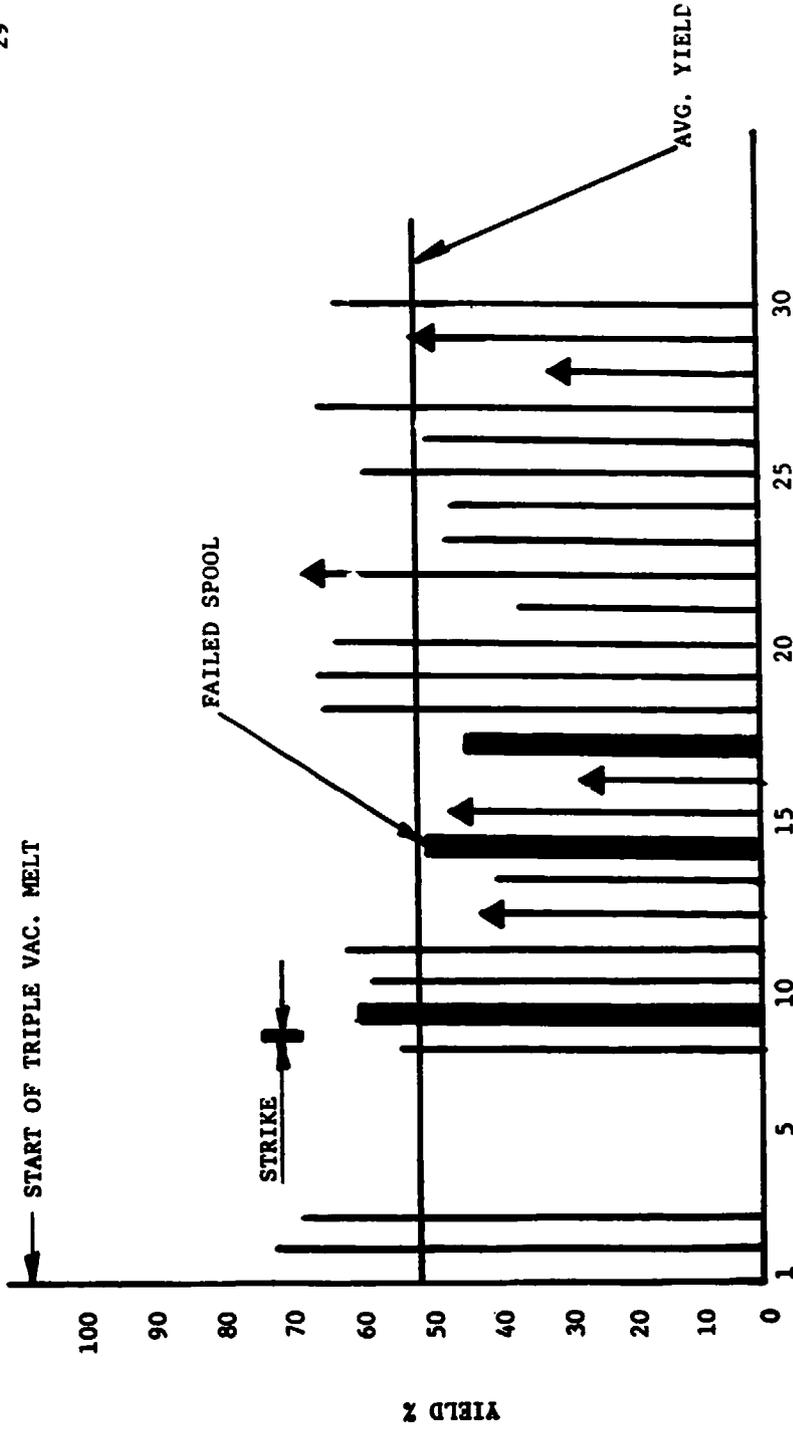
CYCLIC CRACK PROPAGATION FROM THE INCLUSION  
TO SPOOL SEPARATION

## INVESTIGATION AT MILL

- MILL ON STRIKE
- POST STRIKE START-UP PROBLEMS IN INGOT CONVERSION
  - HARD ALPHA INCLUSIONS
  - CENTER BURST (POROSITY)
  - LOW BILLET YIELDS (ULTRASONIC REJECTS)
  - DELAYED SHIPMENTS
- FORGER REQUESTED TO CONVERT INGOTS - EXPEDITE DELIVERY
- AT MILL: OF TWELVE INGOTS CONVERTED AND INSPECTED,
  - 9 CONTAINED ULTRASONIC INDICATION
  - 3 WENT TO FORGER - NO INDICATIONS IDENTIFIED BY HIS ULTRASONIC INSPECTION
  - THE FAILED SPOOL CAME FROM ONE OF THESE THREE INGOTS

▲ HARD ALPHA AND POROSITY FOUND

HT #'S	HT #'S
15	15
22	22
28	28
29	29

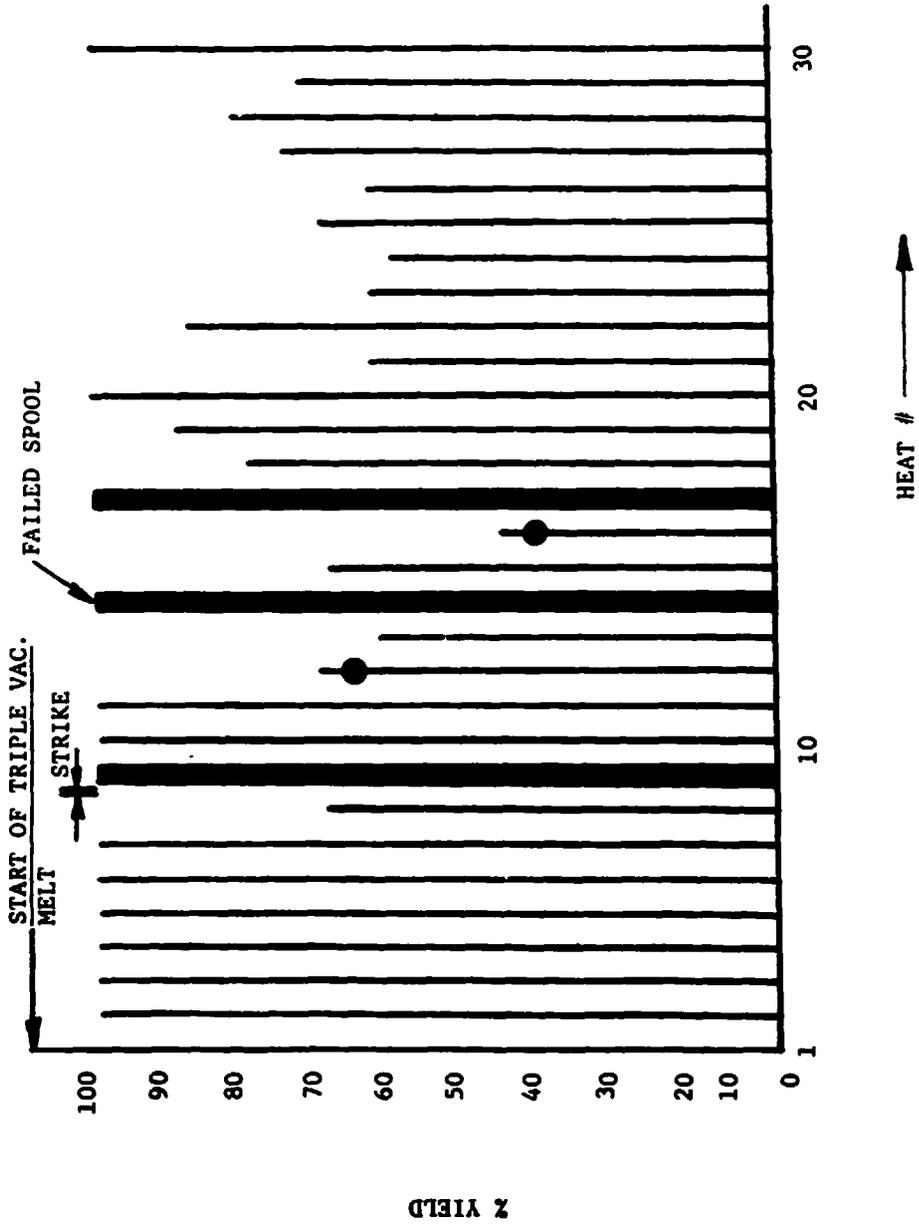


KEY FORGER CONVERSIONS

HEAT #

% ULTRASONIC REJECTS

- FORGER CONVERSIONS
- HARD ALPHA FOUND



**INVESTIGATION CONCLUSIONS:**

- LOW PROCESS YIELDS NOT TRACKED BY MILL OR GE
- NO IMMEDIATE CORRECTIVE ACTION TAKEN
- PROCESS CHANGED AFTER STRIKE (?) START-UP PLAN (?)
- MATERIAL BYPASSED MILL ULTRASONIC INSPECTION -  
FORGER PERFORMED (AN UNAPPROVED SOURCE FOR THIS  
OPERATION)

**LESSON LEARNED**

**VIOLATE A P.Q. CONTROLLED PROCESS,  
AND RISK AN INCIDENT OF SIGNIFICANT  
PROPORTIONS.**

PREMIUM QUALITY MATERIAL TRACK RECORD  
(1972 THROUGH 1976)

	POUNDS OF ALLOY	
	<u>TITANIUM BASE</u>	<u>NICKEL BASE</u>
TOTAL PQ BILLET PRODUCED	10,000,000	10,000,000
HEATS REJECTED AT MELTER	20,000	20,000
BILLET REJECTS AT MILL/FORGER	150,000	150,000
TOTAL PQ PARTS PRODUCED	7,000	16,000
FORGING/ROTOR REJECTS	5	75

GE EXPERIENCE: ONLY ONE SIGNIFICANT INCIDENT

- NONE WHEN PQ ROUTINE RIGOROUSLY FOLLOWED.

MATERIAL PROCESS CONTROL IS THE MOST IMPORTANT KEY  
ELEMENT FOR PREVENTION OF MATERIAL DEFECT RELATED  
ROTOR FAILURES.

## DISCUSSION

### G.J. Mangano, NAPTC

I have one question. Who enforces this procedure -- General Electric, or people that you have at the mill?

### R. Duttweiler, GE-Cincinnati

It is all of them -- steel supplier people and our quality engineering as well as resident people who visit and audit the mills. Every six months we do an audit and every year we renew our agreement as to how things will be processed.

A lot of enforcement is done by the vendor himself; he writes down the rules that he will live by, and we simply audit against them. If he merely depends on us to catch him, he is not doing his job. He is failing to do what we both need to assure premium quality. We have simply set up a self-policing system.

One thing I'd like to add is that this system was forced by engineering on the manufacturer, with great reluctance because manufacturing told us that this would be an extremely expensive way to go. It really hasn't proved to be the case. It has developed into an accepted discipline. At first it was expected that these requirements would add an additional 8-10 per cent to raw materials cost, but it has not amounted to anything near that figure in recent years.